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NOVEL SCHEMES FOR
ELECTROMAGNETIC LAUNCHERS

Final report prepared for
AFOSR

by

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Present Status of Project

A design concept of the coil gun together with its power conditioning unit as an integrated system has been developed. The coil gun operates on the principle of the classical multiphase induction machine, and can therefore be called a linear induction launcher (LIL). It has the advantage of eliminating the need for accurate synchronization of the switching sequence. The projectile consists of a payload housed within a conductive sleeve. Strong centering forces due to the currents in the sleeve provide stability and minimize the magnetic fields within. The power conditioner functions efficiently by using the energy left over from the previous stages to provide energy for later higher-velocity stages.

More work is needed to understand how to better utilize the materials within the limits of the mechanical and thermal stresses; to develop an adaptive control system; to find out how to work with the very high blocking voltage of the power switches, and to construct a demonstration model of a scaled-down LIL machine.

Work Done

During the first year, our effort resulted in the following accomplishments:

1. A feasibility study was made in which scaling laws were developed to provide the dimensions for the launcher within the SDIO requirements.
2. The idea of a traveling-wave synchronous launcher was examined in which a multiphase arrangement of the drive-coil system accelerates a conducting cylindrical sleeve and its inner payload.
3. A power conditioning system for the gun was conceived which consists of several different schemes to be used for the low, medium and high velocity segments of the barrel.

4. Calculations of the decay time of the currents flowing in the projectile sleeve were made and compared with the projectile transit time.
5. A mathematical model was developed for the band of currents moving along the barrel.
6. For the synchronous launcher, the forces on the projectile were analyzed and their values were calculated, taking into account conductivity, air gap, pole pitch, dimensions and material stresses. The results of these preliminary studies motivated the search for alternative schemes.
7. Non-synchronous operation of the gun was investigated to eliminate the need for exact synchronism between the projectile and the wave packet. Reliance was placed on induced, rather than impressed sleeve currents. This resulted in a complete design procedure for a coil gun utilizing the force slip characteristic as the principal law governing the thrust in the gun.
8. The design procedure for the launcher was further developed and optimized, the barrel was sectionalized, and the number of required switches was reduced.
9. A power conditioning circuit was adapted to accommodate the need for merging a number of barrel-sections.

Directions for Further Work

1. To carry out a static experiment for testing force, current and slip relationships.
2. To test and develop power conditioning schemes.
3. To develop an adaptive control scheme to successively adjust system behavior.
4. To build a scaled-down launcher.
5. To study mechanical and thermal stresses by finite element analysis.

Summary

This report describes our first year of work on the design of electromagnetic launchers and of power conditioning systems for them. Our efforts were mainly directed toward the coil gun.

The report consists of a set of four quarterlies, each summarizing the work accomplished during a three month period.

At first, attention centered on a synchronous version of the coil gun; later, on an asynchronous machine. In both cases, the gun barrel is composed of a linear array of coils carrying polyphase currents. These function to create an electromagnetic wave packet, moving with increasing velocity from breech to muzzle, and driving the projectile along with it. The outer portion of the projectile, a conductive sleeve, carries a set of azimuthal currents sinusoidally distributed along its length, and encloses the projectile payload. Selection of a conducting cylinder as the projectile housing was intended to give a smoothly accelerated motion rather than an impulsive one, that would characterize the movement of a projectile consisting of a single coil or of a discrete set of coils. In addition, the sleeve would serve to center the projectile inside the barrel without the need for supporting guides. Also, the shielding effect of the conductive sleeve would eliminate, in principle, any magnetic field from affecting the sensitive electronics of a 'smart' projectile. The power conditioner serves to inject currents sequentially into the barrel coils so that energy can be effectively transferred from them into the projectile.

At an early stage of the project, a feasibility study was carried out in which scaling laws were developed for the length of the barrel and projectile, the thickness of the armature and the relation between the diameter and the pole pitch. It was concluded that, within the constraints of available materials, a 1 kg projectile could be accelerated with a reasonable barrel length, but that the length was proportional to the cube of the muzzle velocity.

The principal problem with operation in the synchronous mode was the need for precise coincidence between the movement of the wave packet and that of the projectile. It soon became evident that, to meet this requirement, it would be necessary to devise a real-time control system that would govern the triggering of the current injection switches. An alternate approach was

therefore investigated that uses a mode of operation similar to that of an induction motor. This is possible because the force-slip characteristic of the coil gun, when operated asynchronously, is very similar to the torque-slip characteristic of a polyphase rotating machine.

The most important accomplishment during our year of study was the development of a detailed procedure for designing a multi-section, inductively-operating coil gun. The calculated projectile velocities and temperatures make us believe that it may really be possible to construct a coil gun of this type; that is, the acceleration of a 1 kg projectile to a velocity of 2 km/s with reasonable efficiency is a first attainable goal. A high degree of energy utilization is obtainable mainly because of a newly-developed power conditioning circuit that operates by transferring energy from capacitor to capacitor simultaneously with the projectile movement (in an open loop controlled circuit). Other major accomplishments were the development of a mathematical model for the spectrum of harmonics currents moving along the barrel; the development and breadboard testing of a power-conditioning system for energizing the coil currents; analysis and calculation of the forces on the projectile; study of the effects of varying the principal parameters of the gun (sleeve conductivity, air gap, pole pitch, sleeve radius and thickness, maximum allowable stress.)

Of course, in the last analysis, the performance of an experimental model of the gun, when energized by a power conditioning system, will be the real test of the feasibility of our proposed solution to the electromagnetic launcher problem.

Detailed summaries of the work performed during each quarter are next presented.

First Quarter - Summary of Work Performed

During the first interval, primary emphasis was placed on a linear synchronous accelerator. This approach to the design of an electromagnetic launcher employs a sequential linear arrangement of coaxial drive coils through which a projectile, housed within an electrically conducting sleeve, is propelled at an increasing velocity from breech to muzzle. The propelling force is due to the interaction between azimuthal currents flowing in the sleeve and the radial component of the magnetic field set up by driver coil currents. This gun design concept is now described in more detail in the following paragraphs.

Initially, in the "start" section of the gun barrel, at the breech, a pattern of azimuthal sleeve currents is impressed by induction. Once established, this current pattern (a sinusoidal distribution along the length of the sleeve) does not change too much because the projectile transit time through the gun, anticipated to be about 2 milliseconds, is less than the time constant for decay of the currents, estimated to be about 3.5 milliseconds. By suitably injecting currents into the array of coils constituting the four sections into which the barrel is divided (the "start" section being the first), a traveling-wave magnetic field packet is created within the barrel. This provides the energy transfer mechanism which, by its interaction with the sleeve currents, propels the projectile with a relatively constant force, and hence with an increasing velocity, through the gun. Transfer of energy from electrical form in the gun power supply, to kinetic form, for the projectile motion, is accomplished differently in the four gun sections, in a manner appropriate to the "start," "low-velocity," "medium-velocity" and "high-velocity" regimes.

The launcher may be visualized as an assembly of two basic types of elements: drive coils and projectile coils. For our understanding, the performance of a single-drive-coil, single-projectile-coil system was analyzed when excited by a voltage spike. The efficiency of energy transfer was calculated, and found, for the ideal case of no resistive losses in either coil, to be equal to the square of the initial coefficient of coupling between the two coils. The effects on efficiency of losses in the drive coil and in the projectile coil were examined. Especially interesting

was the finding that projectile losses gave rise, after the initial part of its travel, to a retarding force (similar to a drag force) for the remainder of its travel. The relative importance depends on the size of the resistive losses. Calculations were made of the mutual inductance M , of the dependence of M on the separation x between the coil centers; and of $\frac{dM}{dx}$, which is a measure of the accelerating force on the projectile for fixed currents in the two coils.

For the single-coil system, an important question that arises is: if the driver coil moves transversely, off-axis, during its travel, will there be a restoring force or not? This question of transverse stability was first thought about and then experimentally studied in a simple system. It was found that, when the coils were co-planar, the system is stable; however, during the coil motion, the arrangement soon becomes unstable after the moving coil has been driven a short distance beyond the driver.

Next, the idea of a traveling-wave synchronous launcher was examined, in which the sequence of coils constituting the gun barrel is excited to achieve a relatively non-impulsive, smooth accelerating force applied to a cylindrical sleeve projectile, rather than to a single driven coil or to a set of driven coils. An important aspect of this idea is that a set of circular, azimuthal currents is induced on the sleeve during the first part of its motion so that the traveling-wave magnetic field packet may subsequently accelerate it. Hence, it was essential to estimate the decay time of these currents so that a comparison could be made with the transit time through the gun. This estimate was made first for a planar sleeve model, and then for a cylindrical sleeve. The two results were nearly in agreement, yielding a time constant of about 3.5 ms for the dimensions chosen and for a copper sleeve. This exceeds the anticipated transit time of about 2 ms, and hence offered us encouragement that the overall general concept was not an unreasonable one.

Second Quarter - Summary of Work Performed

During the second quarter, our work continued to focus on the linear electromagnetic launcher.

An important question, first raised in the previous quarter, was: How does the decay time of the sleeve currents compare with the transit time of the projectile through the gun? Obviously, if the currents decay too quickly, there will be no thrust available to accelerate the projectile during the latter part of its transit through the barrel. The time constant for the (copper) sleeve was estimated to be 3.5 milliseconds in the previous quarter, compared to a transit time of 2 ms. During this quarter, a more careful re-calculation of this quantity was made for the cylindrical model (the new result was 3.33 ms instead of 3.74 ms), and an additional calculation was made for a smaller projectile diameter (5 cm - the result was 3.53 ms). We concluded that the radius of the projectile sleeve has only a minor influence on the decay time, and that the previous estimate of 3.5 ms was (perhaps fortuitously) a very good one.

To gain additional insight into the question of decay time, a different model of the projectile was employed: it was viewed as a long coil; that is, a lumped circuit rather than a field approach was used. A coil has resistance R and inductance L , with an associated time constant of L/R . This approach is described in detail. The results suggest that mutual inductance effects give a decay rate in the center of the sleeve that is faster than that at the ends of the sleeve. Subsequently, the same approach was used to study the wave-shape of the current in the coils that compose the barrel. There, currents are switched on sequentially in the coils at the front end of the excited-coil group, and switched off at the trailing end of the group. Ideally, they are sinusoidal for exactly three cycles, for as long a time as they flow; actually, they are not. The results of this study were presented in the third quarterly report.

In our launcher, the methods used to switch the coil currents are different, depending upon whether the coils are located in the low, medium, or high-velocity section of the barrel. For the medium-velocity portion, an analysis and design of a six-section model is presented, with resistors

used to represent energy transfer to the projectile during its travel through the center of the barrel. The basic idea of the circuit is described in detail, with magnetic coupling among the six coils assumed to be absent. The construction of a breadboard model was started so that the circuit behavior could be experimentally observed. It was planned, later, to position the coils to gradually increase the coupling in order to simulate a more realistic situation. The experimental circuit behavior is described in the third quarterly report.

In order to calculate forces, losses and efficiency, two mathematical models were constructed for the distribution of currents along the barrel. One, an integral representation, was based on the Fourier transform. The second, a discrete representation, was based on Fourier series. The current in each coil was assumed to be sinusoidal, but to last for only a few complete cycles. Then, to check the validity of the representation based on Fourier series, a set of parameters was chosen, and the current distribution along the barrel calculated for a number of different values of time. Also, the spectral composition of the distribution was calculated. The graphs depicting the current distribution clearly show a travelling wave, and suggest that the original formulas and the program which was used to develop the graphs are both correct.

In a separate, self-contained section intended to be the core of a published paper, the basis for a design procedure for the launcher was presented; those aspects of the work to date underlying the design were briefly summarized; and the effects of asynchronous wave components were considered. Also discussed were: how the design is affected by mechanical stress limitations; thermal diffusion velocity; temperature rise of the projectile; how the barrel length depends on the muzzle velocity; and how efficiency is affected by muzzle velocity.

Third Quarter - Summary of Work Performed

The work accomplished during the third quarter again focussed on the coil gun, and consisted of four main parts:

(a) For the currents flowing in the barrel coils, waveforms were plotted for the case where 18 coils were sequentially energized with 60° delay between firings. Each coil was allowed to oscillate for exactly three periods. The purpose was to see whether the currents actually were sinusoidal or not. This simulation suggests what might occur in a practical situation. This work was done for three different spacings between adjacent coils. The results indicate that, in the first few and in the last few coils on a long barrel, the currents would not be sinusoidal, but along most of the barrel length, the waveform would be quite good.

(b) A breadboard circuit was built to simulate the medium-velocity section of the barrel. It was a six-coil scaled-down version with no coupling between the coils. The goal was to test the circuit, to gain insight into its behavior and to make an estimate of the efficiency of the power conditioner. Voltage waveforms across each capacitor and currents in each coil were recorded. For this experimental circuit, in which the currents flowed for only one half-cycle, and in which the peak currents increased in value in succeeding coils, it was estimated that the one-shot energy-usage efficiency was about 56%. In a practical situation, in which the peak currents in the barrel coils would be kept constant to make the thrust on the projectile fixed, and in which there are repeated firings, it is believed that the efficiency would be considerably higher.

(c) An analysis of a planar model of an asynchronous driver-projectile system was carried out. For this case, the projectile velocity V was lower than the magnetic wave velocity V_s ; that is, there was a relative velocity between the projectile and the wave. The force was calculated that is exerted on the projectile by the action of the magnetic field on the projectile currents. This mode of operation is very similar in concept to that of an induction motor. The results are presented in the form of a series of graphs showing the force as a function of the slip $(V_s - V)/V_s$ between the projectile and wave velocities. Parametric studies of the effects of varying the synchronous speed

V_s , conductivity, gap width and pole pitch were made. The behavior of the system was found to be qualitatively and quantitatively similar to that of an induction motor. This similarity was used as the basis for developing a design procedure for a coil gun operating in the asynchronous mode.

(d) A procedure for designing a coil gun to operate in the asynchronous mode was developed. It is based on the assumption that the gun has a force-slip characteristic that is identical with the torque-slip characteristic of an induction motor. The gun is seen as consisting of a number of separate sections; each may have a different synchronous speed, and operates, from projectile entry to projectile exit from the section, on the portion of the force-slip characteristic that lies above a chosen minimum force F_0 . The principal design parameter is the ratio F_0/F_c , where F_c is the maximum force. This approach was extremely promising, and was actively pursued.

The principal importance of the asynchronous approach is that it removes the need for precise synchronism between the magnetic wave packet and the projectile. This permits pre-sequenced gating of the switches activating the barrel coils, so that closed loop operation is not necessary.

Fourth Quarter - Summary of Work Performed

The work accomplished during the last quarter of our first year consists of four parts.

First, a complete design procedure, initially described in the third quarterly report, was developed based on the theory of steady-state operation of the polyphase induction motor, which the launcher resembles in many respects. This step-by-step procedure develops the design of a multi-section gun which will accelerate a projectile of given mass to achieve a specified muzzle velocity. Essential parameters that enter into the design are: sleeve dimensions and conductivity; specific heat; ability to withstand mechanical and thermal stress; maximum acceleration. The design calculates the total barrel length, the optimum length and frequency for each section, the transit time, the projectile temperature rise and estimates the losses. A sample design is given to illustrate the procedure for a 1 kg projectile with an aluminum sleeve, a muzzle velocity of 2000 m/s and entry speed of 200 m/s, 8 sections, and maximum acceleration of 10^6 m/s^2 . The corresponding barrel length is 2.7 m with a sleeve temperature rise of 332° C .

Second, a performance analysis of the launcher was made. It examined the question of how to determine the launcher dimensions to make best use of the mechanical, electrical, and thermal properties of materials, while minimizing losses and maximizing conversion into kinetic energy. A planar model of the launcher, and a Fourier series representation of the currents and fields, were used as the basic tools to carry out the work. Parametric studies show graphically the effects on the launcher length and operation of: muzzle velocity; sleeve length, thickness and radius; pole pitch; allowable mechanical and thermal stress; barrel coil thickness. We hope to construct an experimental model during our second year of work to the extent allowable by our funding. This will enable us to demonstrate how closely the performance of the device we build by our design method agrees with predictions.

Third, an initial attempt was made to address the control problem. Since the transit time of the projectile through the gun is so short, it is not feasible to use a closed-loop real-time scheme to control switch triggering. Instead, a more practical open-loop alternative was conceived which

uses a pre-scheduled firing sequence together with an adaptive control scheme. Gun performance data is taken during each shot, and is then processed to re-schedule subsequent firing sequences . In this way, by making small corrections before each shot is fired, a self-adjusting system may be made.

Fourth, a series of experiments was performed with a small two-stage coil gun. The driver consisted of two stationary 5-cm-diameter, separately- excited coils, and the projectile of a 3.5-cm length of thin-walled copper tubing. The driver coils were sequentially energized by allowing 50 μ F condensers, at 3 kV, to discharge through the coils. Velocity reached by the projectile was determined shortly after it had passed through the driver by measuring the time interval between two fixed points in its guiding PVC tube. Of great interest was the clear demonstration of how critical was the initial location of the projectile at the time of firing if a high velocity of the projectile was to be achieved. We hope to avoid this problem in our gun designs by using a sleeve projectile, polyphase excitation of the barrel and an asynchronous mode of operation.